Neutrino Physics Program Overview

Gina Rameika

URA Visiting Committee

April 22, 2005

Outline

- Introduction
- *Program Evolution*
- *Recent Highlights of the Current Program*
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  - *MINERvA*
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  - *Staff*
- *Long Term Scenarios*
- Summary and Conclusions

Introduction

I recently came across a paper, whose introductory paragraph began with the following questions…

- Are neutrino masses different from zero?
- What kind of particles-Dirac or Majorana-are the neutrinos with definite masses?
- Does lepton mixing analogous to quark mixing take place?
- Do neutrinos that take no part in the standard weak interaction (the so-called sterile neutrinos) exist?

Followed by the statement…

- The answers to these and many other fundamental questions of neutrino physics are not yet known to us. Numerous experiments are being performed and prepared at present in dozens of laboratories around the world with the aim of finding answers to them…
  - Bilenky and Petcov, July 1987
    - Reviews of Modern Physics
- At the time these experiments were being motivated by the "smoking guns" pointing towards
  - Missing dark matter
  - Missing solar neutrinos
  - Anomalies in the detection of atmospheric neutrinos

Neutrino Oscillation Searches proposed for Fermilab

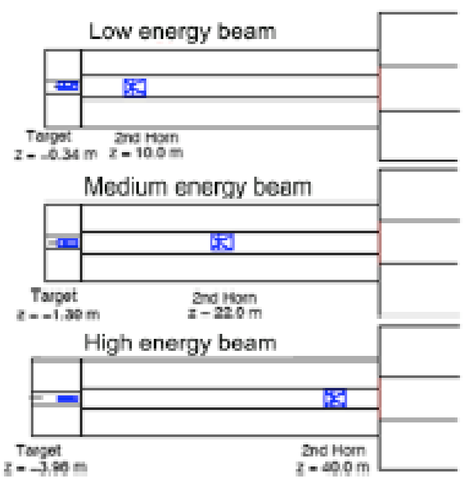
- Physics at Fermilab in the 1990's
  - August 15-24, 1989 Breckenridge, Colorado
  - Oscillation Sub-group within the Electroweak Group

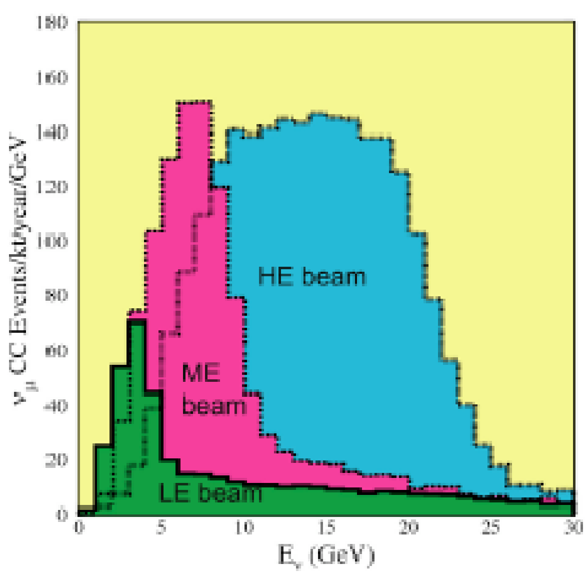
…. consider the possibility of searching for $\nu_\mu \rightarrow \nu_\tau$ oscillations using a high-rate neutrino beam. The basis of this new plan is the possibility of using the proposed proton synchrotron, the Main Injector, which is the center of the Phase II upgrade proposal. With this device the proton beam would be extracted every 3 seconds at 150 GeV at intensities which are potentially many times 10^{13} protons.

- Long baseline proposals
  - MI beams to Soudan 2 or IMB
- Snowmass 1994
  - Open letter from J. Peoples to Physics community
    - Outlined Fermilab plan for short and long baseline experiments using a neutrino beam from the Main Injector
    - Time scale for starting 2000…

Program Evolution

- 1993 - Began serious NuMI "project definition"
  - Short baseline tau appearance (E803 a.k.a. COSMOS)
  - Long baseline to Soudan 2 detector (P-822)
  - Design highest energy neutrino beam possible with MI
- 1994 - several LBL EOI's join to form MINOS
- 1998 -
  - NuMI Construction Project begins
  - Super-K indicates small Δm^2
  - COSMOS experiment withdrawn
  - NuMI designs flexible energy option
- 2005 - NuMI operation begins with Low Energy Neutrinos





Hindsight is 20-20, but we need to plan looking forward…

Surprises

VOLUME 75, NUMBER 14 PHYSICAL REVIEW LETTERS 2 OCTOBER 1995

Candidate Events in a Search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillations

C. Athanassopoulos,[12] L. B. Auerbach,[12] D. A. Bauer,[3] R. D. Bolton,[7] B. Boyd,[9] R. L. Burman,[7] D. O. Caldwell,[3] I. Cohen,[6] B. D. Dieterle,[10] J. B. Donahue,[7] A. M. Eisner,[4] A. Fazely,[11] F. J. Federspiel,[7] G. T. Garvey,[7] M. Gray,[3] R. M. Gunasingha,[8] V. Highland,[12,*] R. Imlay,[8] K. Johnston,[9] W. C. Louis,[7] A. Lu,[3] J. Margulies,[12] K. McIlhany,[1] W. Metcalf,[8] R. A. Reeder,[10] V. Sandberg,[7] M. Schillaci,[7] D. Smith,[5] I. Stancu,[1] W. Strossman,[1] M. K. Sullivan,[4] G. J. VanDalen,[1] W. Vernon,[2,4] Y-X. Wang,[4] D. H. White,[7] D. Whitehouse,[7] D. Works,[12] Y. Xiao,[12] and S. Yellin[3]

[1]*University of California, Riverside, California 92521*
[2]*University of California, San Diego, California 92093*
[3]*University of California, Santa Barbara, California 93106*
[4]*University of California Intercampus Institute for Research at Particle Accelerators, Stanford, California 94309*
[5]*Embry Riddle Aeronautical University, Prescott, Arizona 86301*
[6]*Linfield College, McMinnville, Oregon 97128*
[7]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545*
[8]*Louisiana State University, Baton Rouge, Louisiana 70803*
[9]*Louisiana Tech University, Ruston, Louisiana 71272*
[10]*University of New Mexico, Albuquerque, New Mexico 87131*
[11]*Southern University, Baton Rouge, Louisiana 70813*
[12]*Temple University, Philadelphia, Pennsylvania 19122*

(Received 19 April 1995; revised manuscript received 12 June 1995)

A search for $\bar{\nu}_e$'s in excess of the number expected from conventional sources has been made using the Liquid Scintillator Neutrino Detector, located 30 m behind the Los Alamos Meson Physics Facility beam stop. The $\bar{\nu}_e$ are detected via $\bar{\nu}_e p \rightarrow e^+ n$ with e^+ energy between 36 and 60 MeV, followed by a γ ray from $np \rightarrow d\gamma$ (2.2 MeV). Using strict cuts to identify γ rays correlated with e^+ yields 9 events with only 2.1 ± 0.3 background expected. A likelihood fit to the entire e^+ sample results in a total excess of $16.4^{+9.7}_{-8.9} \pm 3.3$ events. If attributed to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, this corresponds to an oscillation probability of $(0.34^{+0.20}_{-0.18} \pm 0.07)\%$.

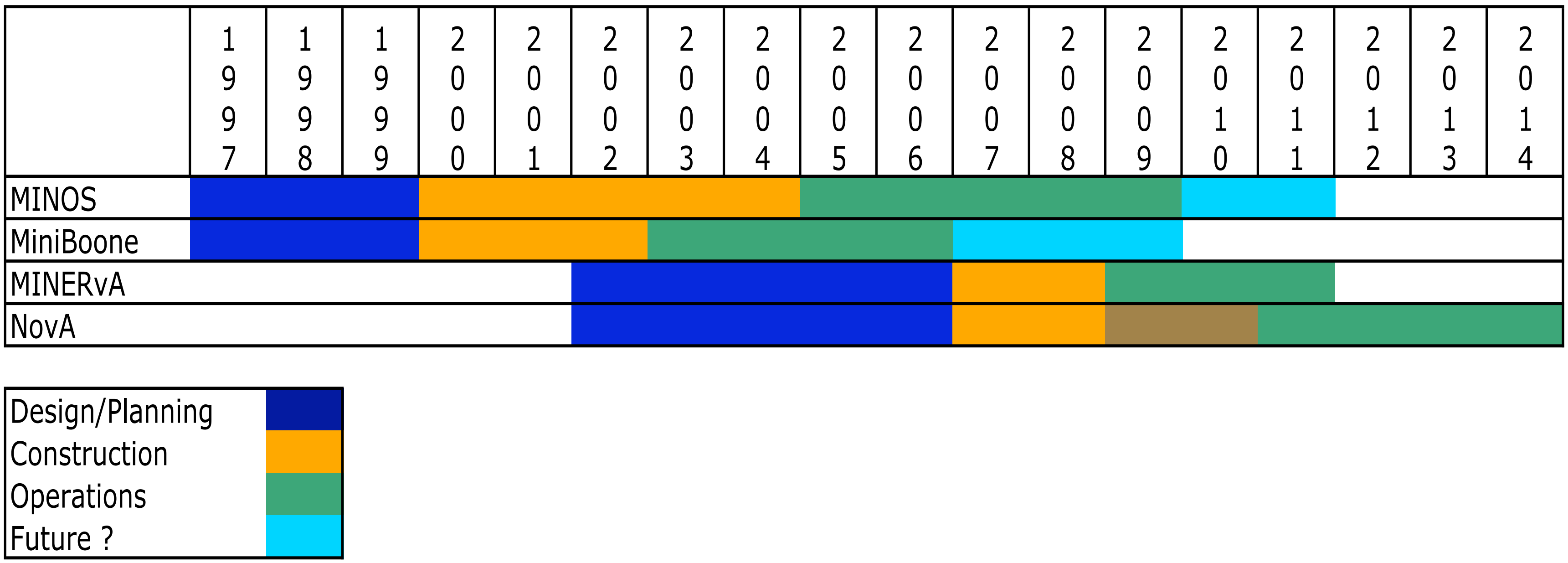
PACS numbers: 14.60.Pq, 13.15.+g

The Fermilab Program

- MiniBooNE
  - 1 GeV Neutrinos produced by the Fermilab Booster
  - 800 ton mineral oil cherenkov detector, @ L ~ 500 m
  - $\nu_\mu \rightarrow \nu_e$ appearance in LSND signal region
  - Operating since 2003, Data Analysis
- MINOS
  - ~ 2 GeV Neutrinos produced by 120 GeV Main Injector protons
  - ~5.4 kton detector @ L = 735 km; ~1 kton detector @ ~ 1 km
  - ν_μ disappearance in atmospheric region
  - Operations begin in 2005, awaiting significant data
- MINERvA
  - NuMI Neutrino Beam
  - 5 ton fully active fine grained detector, upstream of MINOS Near
  - Comprehensive program of low energy neutrino scattering physics
  - R&D, Technical Design
- NOvA
  - NuMI Off-Axis Neutrinos @ θ = 16 mrad (13 km) and L = 810 km
  - 30 kton fully active liquid scintillator
  - ν_e appearance to measure $\sin^2 2\theta_{13}$
  - R&D, Technical Design

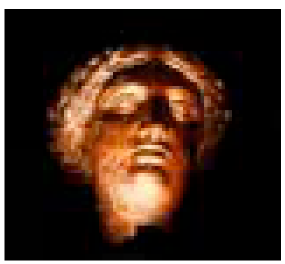
Time Scales

Our program has been going on for more than a decade, and with proper funding will continue for at least another…



Collaborations

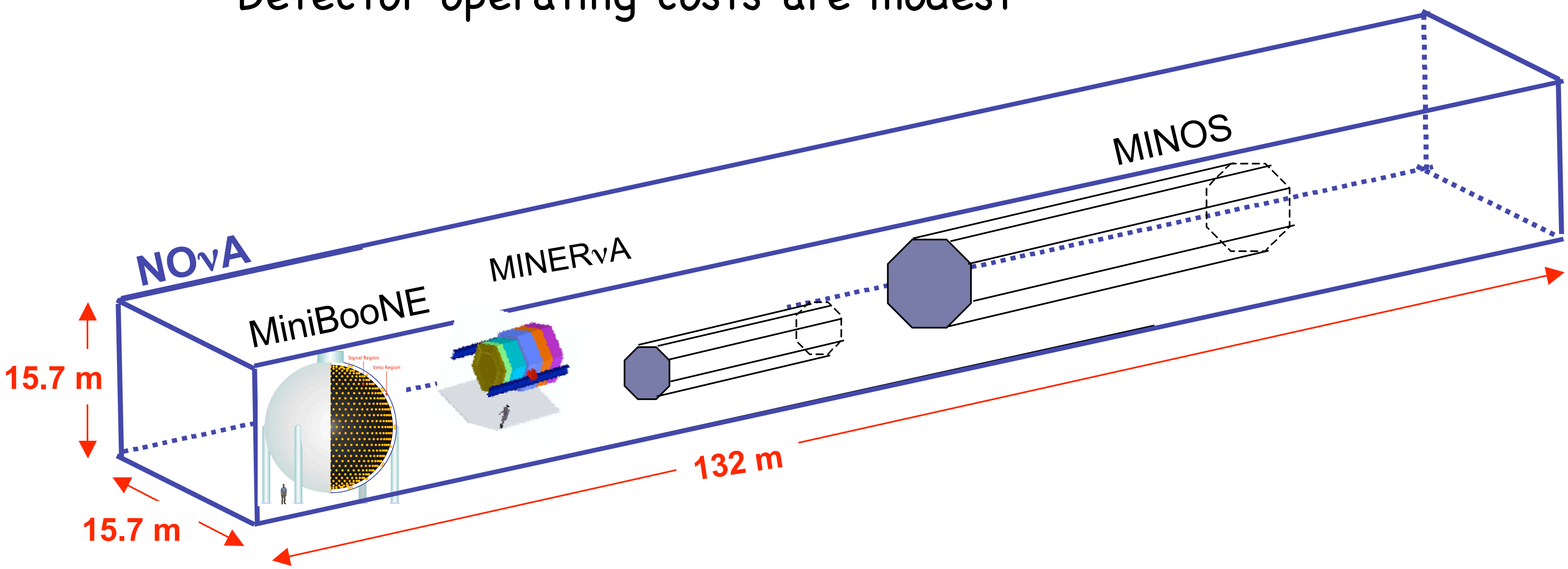
Neutrino experiment collaborations are relatively small by today's standards…..



	MiniBoone	MINOS	Minerva	Nova
# of Institutions	15	32	17	29
# of Authors	77	181	65	127
# of Fermilab Authors	19	29	8	27
# of Fermilab Scientists	9	22	4	15

Budgets

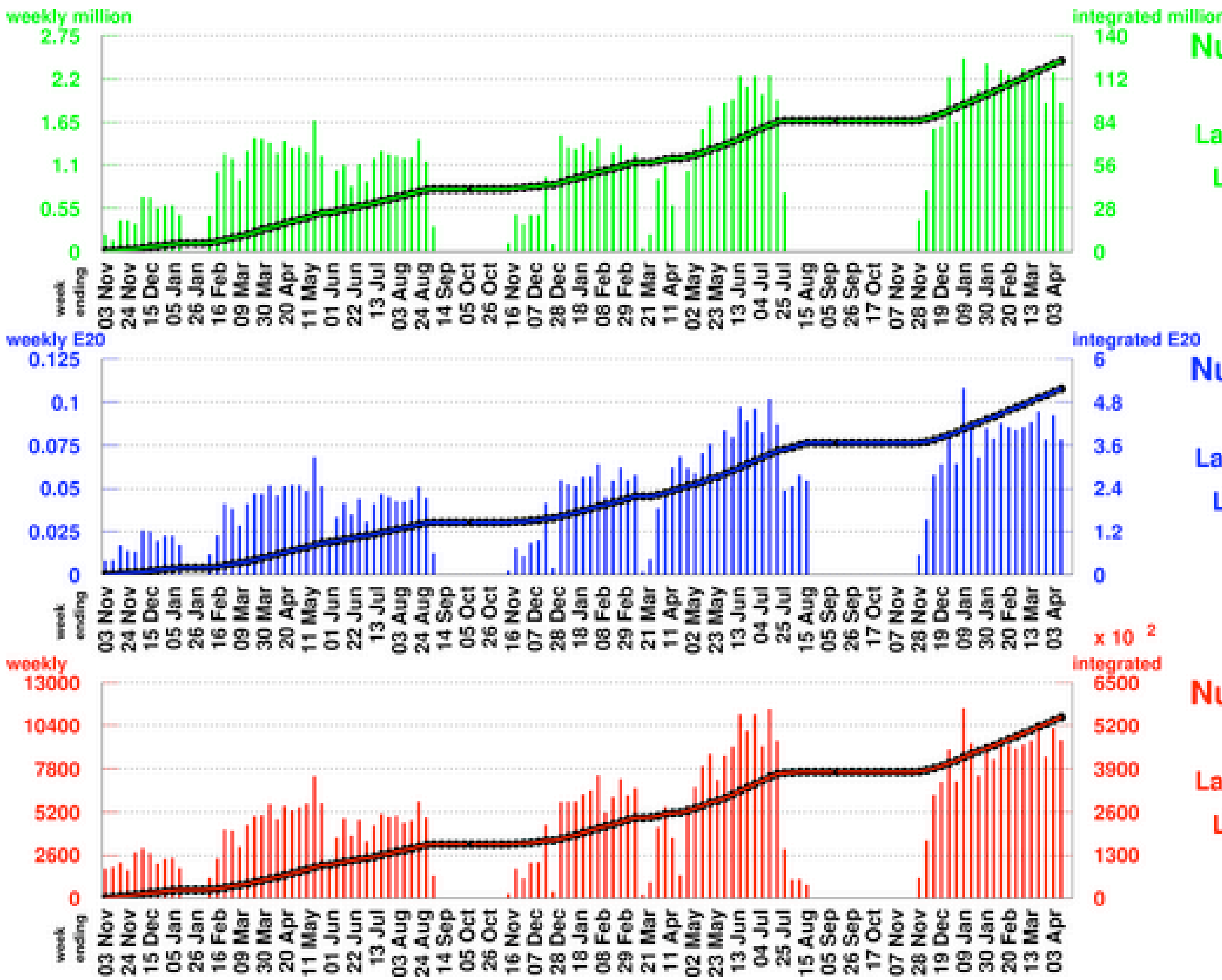
- The detectors have a large range of size which drives construction costs
  - MiniBooNE, Minerva : ~$10M
  - MINOS : ~$40M
  - NOvA : ~$100M + 50% contingency
- The detectors are simple (few systems) and robust
  - Detector operating costs are modest



Recent Highlights

- MiniBooNE
  - 5e20 Protons on Target milestone : April 3, 2005
  - > 500k neutrino interactions to date
- MINOS
  - First NuMI Beam : December 2004
  - First Near Detector Neutrinos : January 2005
  - First Far Detector Neutrinos : March 2005
  - (Low-light) Target cooling water leak : March 23, 2005
- MINERvA
  - Director's Review of cost and schedule : January 2005
  - Project Management organization established
  - FY05 R&D Budget plan
- NOvA
  - Technology choice : January 2005
    - 30 kton all active liquid scintillator in plastic extrusions
  - Stage I Approval : April 2005
  - FY05 R&D Budget plan

MiniBooNE



Number of Horn Pulses

To date: 123.71 million

Largest week: 2.46 million

Latest week: 1.89 million

Number of Protons on Target

To date: 5.1729 E20

Largest week: 0.1084 E20

Latest week: 0.0784 E20

Number of Neutrino Events

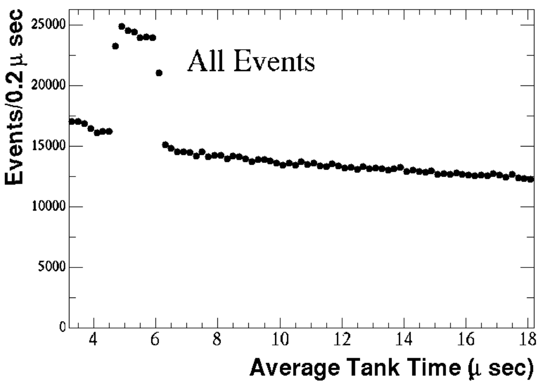
To date: 545598

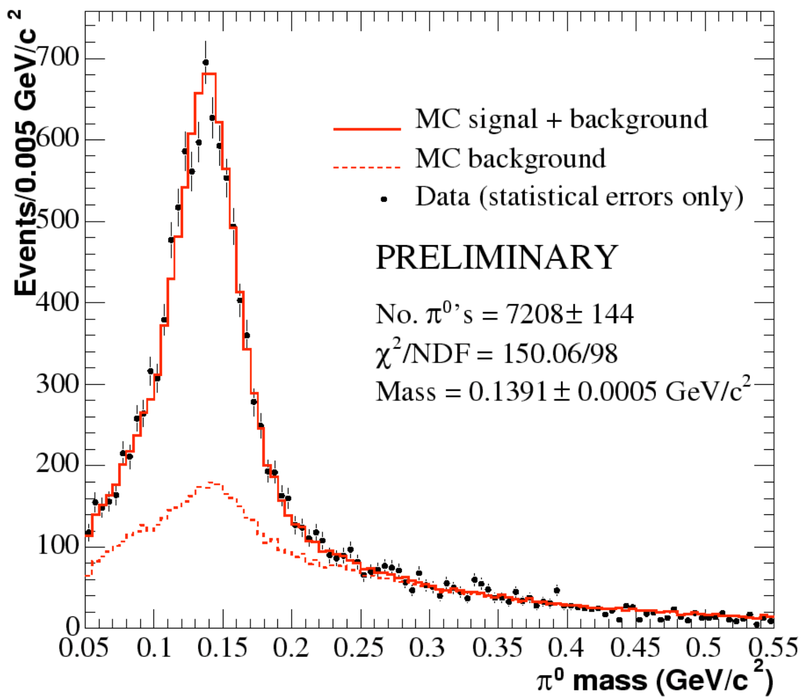
Largest week: 11447

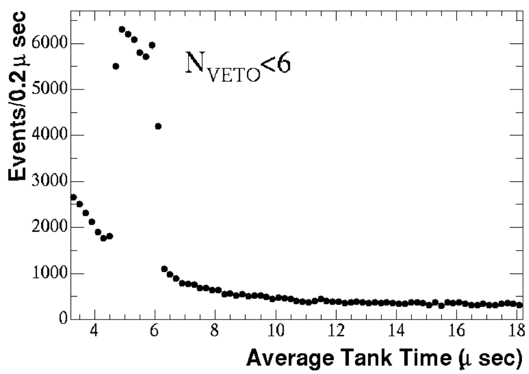
Latest week: 9518

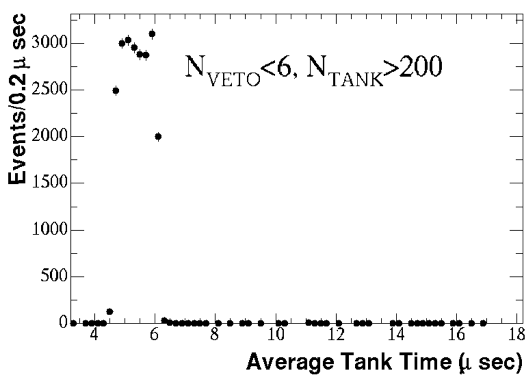
Nov 2002

MiniBooNE







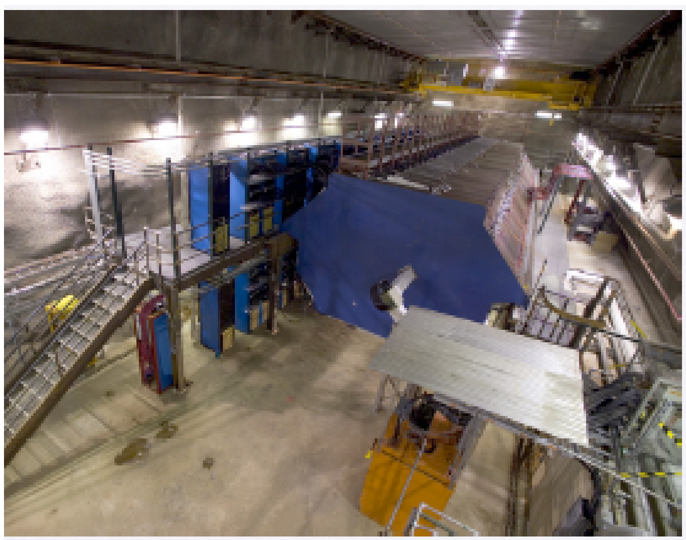


MiniBooNE has 9 graduate students;
One completed thesis :
M. Sorel, "Search for Sterile Neutrinos Using the MiniBooNE beam";
A second thesis is due shortly.

MINOS

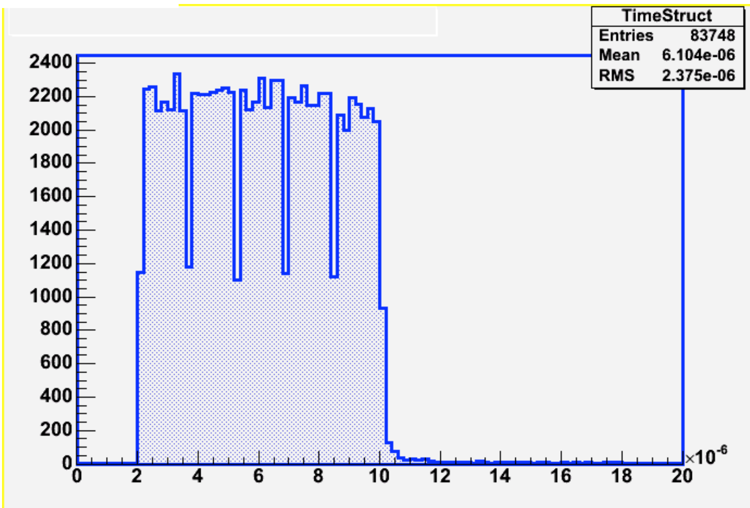
Far Detector

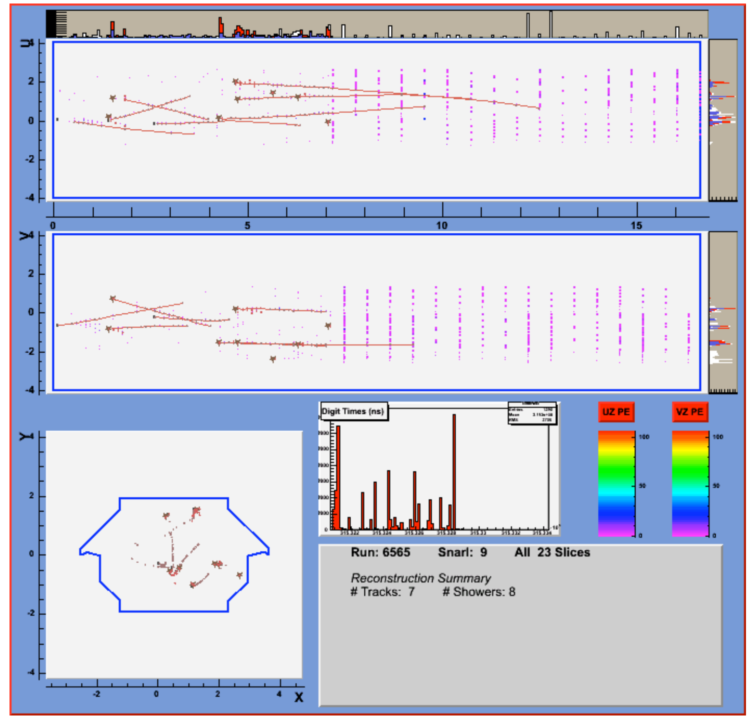
Near Detector



- Far Detector
  - Completed in August 2003
  - Running routinely with cosmic rays and collecting atmospheric neutrino data
- Near Detector
  - Installation completed in November 2004
  - Completely commissioned on cosmic rays prior to beam start up

MINOS Near Detector

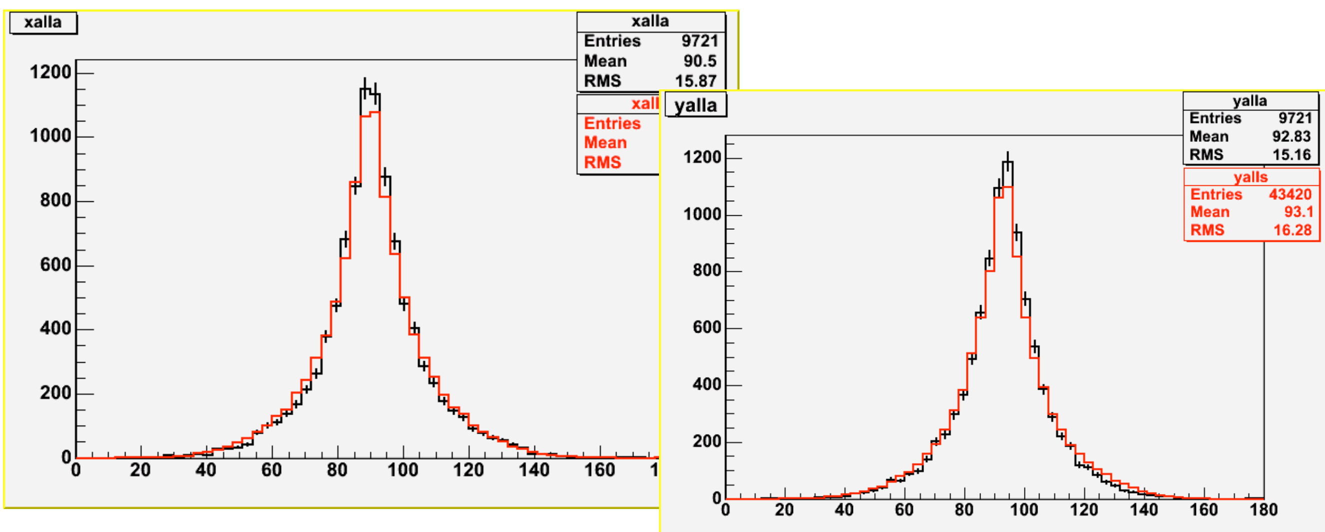


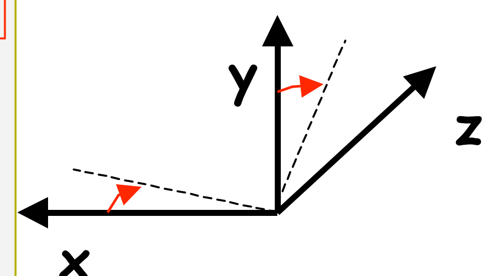


- 8 micro sec spill consisting of 5 - 1.6μs booster batches
- Events recorded within a 20 micro sec window
- Many neutrino interactions per spill
- Time and space used to separate individual events

MINOS Near Detector

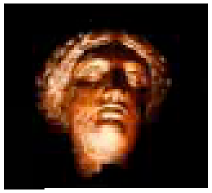
- 11,000 Neutrino interactions per day in a 1m radius, 4 m long "fiducial volume" (2.5e13 @2 sec rep rate)
- Also detect muons from interactions in the rock absorber, and neutrino interactions throughout the calorimeter (upstream half of detector; downstream half is "muon spectometer" with multiplexing)
- Event reconstruction
  - Track, shower or track + shower
  - Measure track angles, track length, shower energy, …



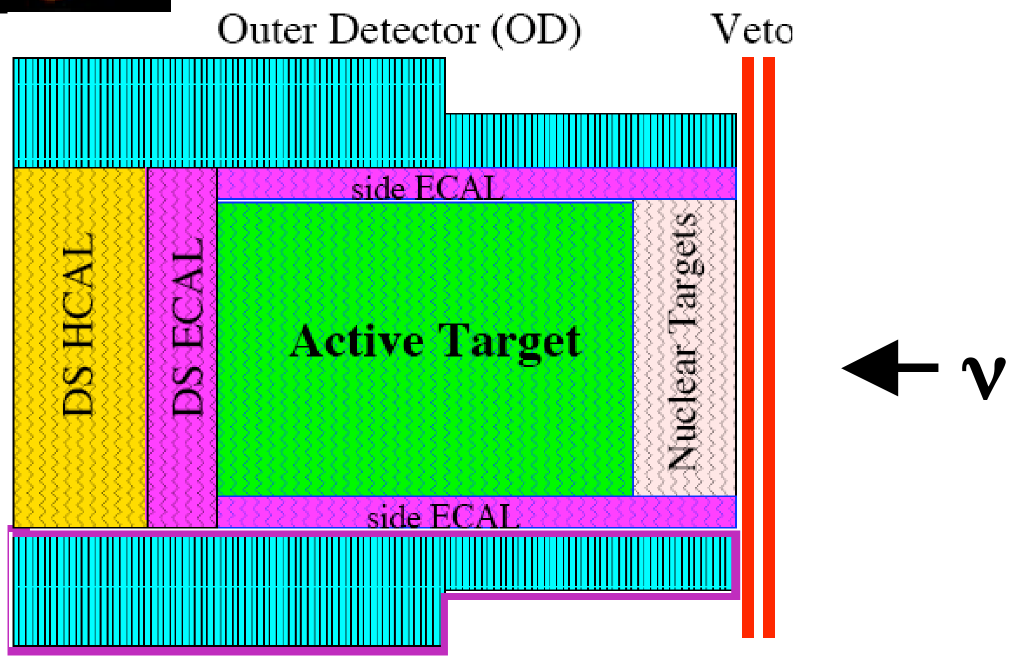


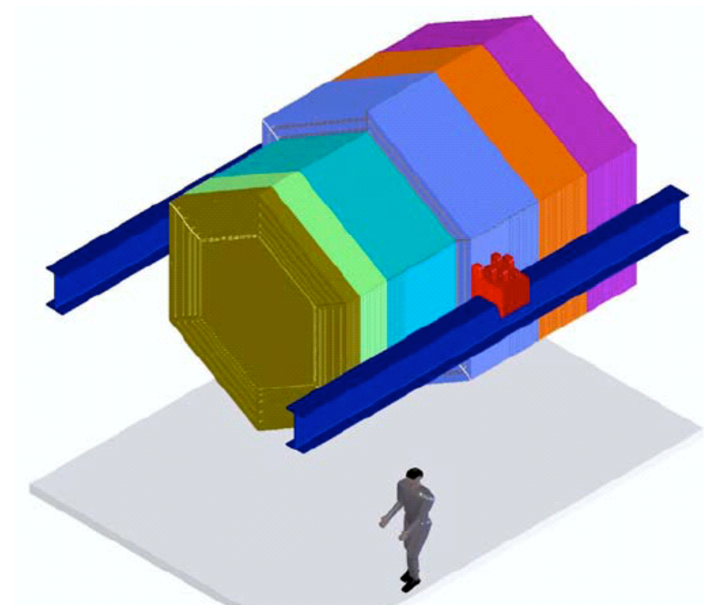
MINOS Far Detector

- Expect ~1 neutrino interaction per day in the fiducial region (2 in the whole detector) assuming no oscillations and 2.5×10^{13} POT every 2 sec in a "16 hour" day.
- In March we ran ~1 week at 1.2×10^{13} @ 3 sec repetition rate and in total accumulated ~ 6×10^{17} POTs.
- For these POTs we expect ~ 1-2 neutrino events in the fiducial region, not enough to accumulate trustworthy rates, BUT
- We do have a "few" candidates.

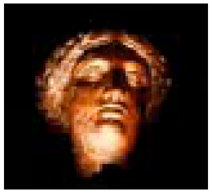


MINERvA





- Fine grained, fully active neutrino detector
- Active target
  - 5t total, > 3t fiducuial
- Calorimeters
  - Pb, Fe targets ~ 1 ton each
  - Magnetized side and downstream tracker/calorimenter
- Installed in NuMI Near Detector Hall upstream of MINOS Near Detector



MINERvA

For 9e20 POT (~ 3 years) :
7e20 in LE; 1.2e20 in ~ME; 0.8e20 in ~HE

ν_μ Event Rates per fiducial ton

Process	CC	NC
Quasi-elastic	82 K	27 K
Resonance	156 K	48 K
Transition	164 K	52 K
DIS	336 K	100 K
Coherent	7 K	3.5 K
TOTAL	745 K	228 K

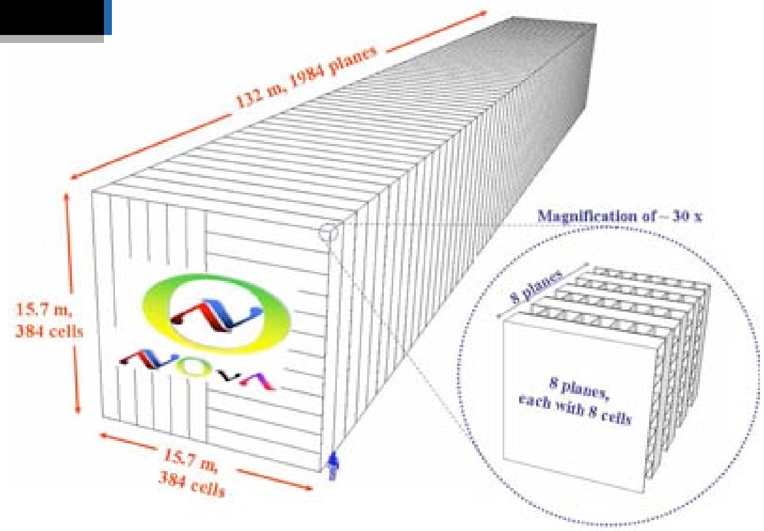
Typical Fiducial Volume = 3-5 tons CH, 0.6 ton C, ≈ 1 ton Fe and ≈ 1 ton Pb

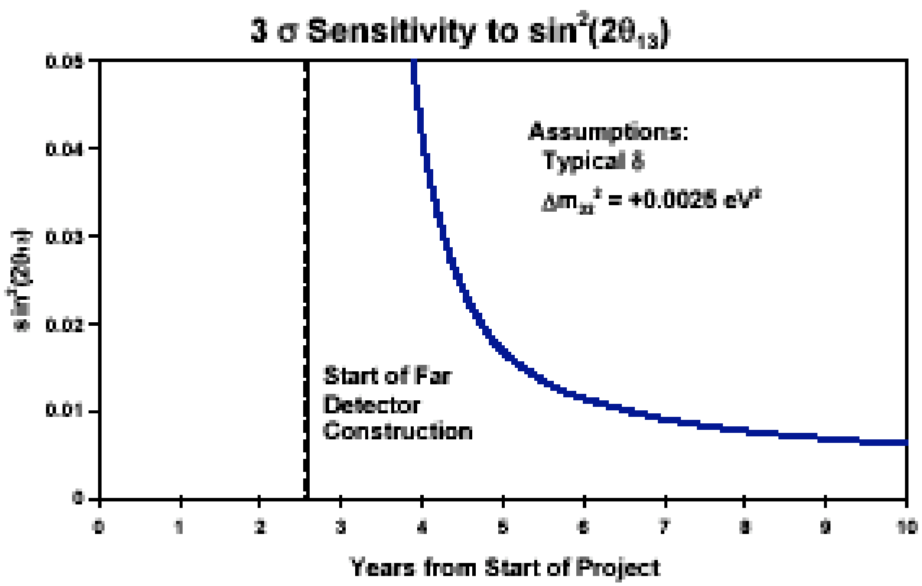
2 - 3.5 M events in CH
0.5 M events in C
.75 M events in Fe
.75 M events in Pb

Main Physics Topics with Expected Produced Statistics

- Quasi-elastic — 250-400 K events off 3-5 tons CH
- Resonance Production — 470 K total, 350 K 1π
- Coherent Pion Production — 20 K CC / 10 K NC
- Nuclear Effects — C:0.5 M, Fe: .75 M and Pb: .75 M
- DIS and Structure Functions — 1 M DIS events
- Strange and Charm Particle Production — > 60 K fully reconstructed events
- Generalized Parton Distributions — few K events

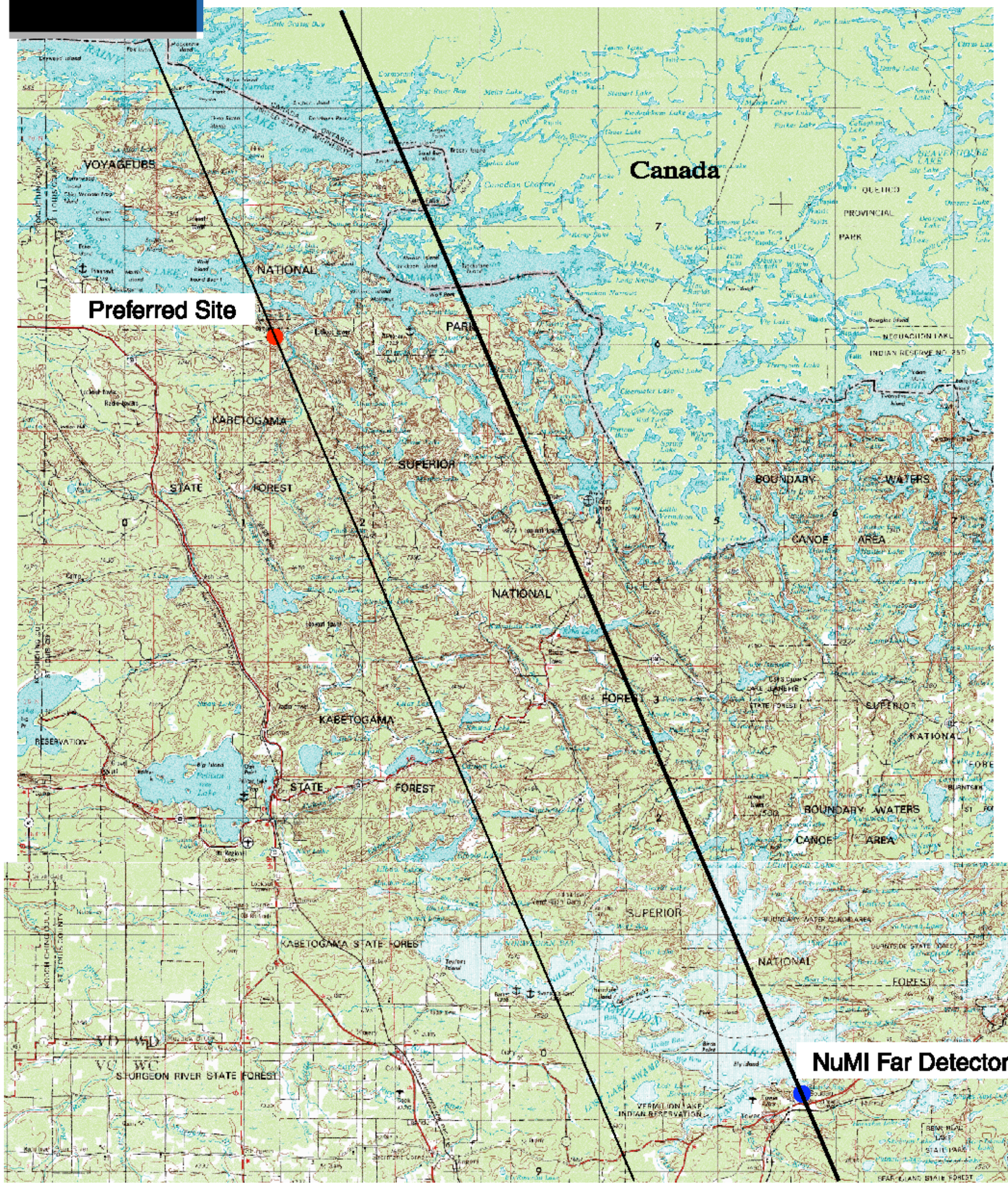
NOνA



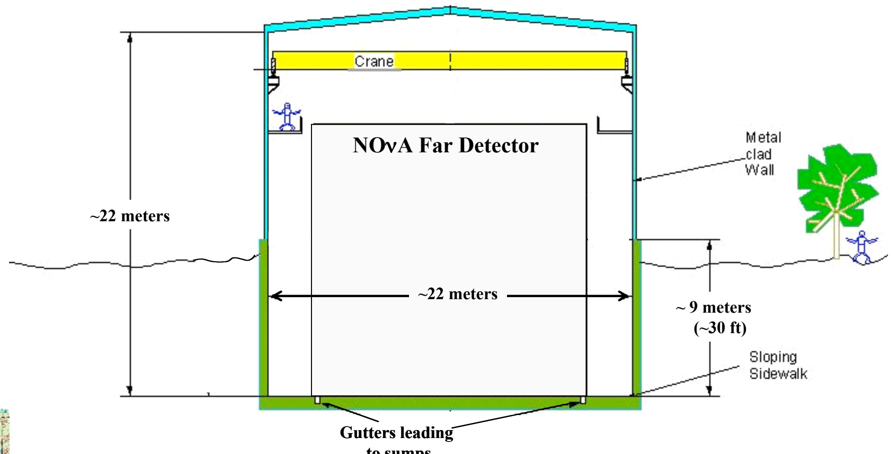


- 30 kton totally active detector
  - 23,808 Titanium dioxide loaded PVC extrusions
    - 761,856 cells
    - 3.9 cm wide, 6-cm deep
  - 23,885 tons of Liquid scintillator
  - 25,629 km of Wave-length-shifting fibers
  - 32 pixel Avalanche photodiode readout
- ~2000 ν_μ CC events per 7e20 POT ($\Delta m^2 = 2.5 \times 10^{-3}$)
- Electron ID efficiency 24%
- for $\sin^2 2\theta_{13}$ ~ 0.1 would see ~150 ν_e interactions in 5 years

NOνA



Preferred site at Ash River :
(just outside Voyager National Park)
~15 km east of Highway 53,
~ 40 km e-s-e of International Falls,
~ 80 km north of Tower-Soudan



Building designed for full containment of the liquid

NOvA Cost Estimate

WBS	Description	Base Cost (K$)	Overhead (K$)	Contingency (K$)	% Contingency	Sub-total (K$)
1.0	**Far Detector**					
1.1	Active Detector					
	1.1.1 PVC Modules + Assembly	19,513	2,184	7,085	33%	28,782
	1.1.2 Liquid Scintillator + handling	24,063	59	6,187	26%	30,309
	1.1.3 Waveshifting Fiber	13,400	8	4,022	30%	17,430
	1.1.4 EDIA	1,680	470	860	40%	3,011
1.2	Electronics, Trigger and DAQ	7,853	803	4,756	55%	13,412
1.3	Shipping & Customs Charges	4,799	960	1,200	21%	6,958
1.4	Installation	7,530	1,963	4,048	43%	13,541
	Far Detector Sub-total	**78,837**	**6,446**	**28,159**	**33%**	**113,442**
2.0	**Near Detector**	**1,678**	**470**	**945**	**44%**	**3,092**
3.0	**Building and Outfitting**					
3.1	Site Work	5,275	158	4,075	75%	9,509
3.2	Building	11,532	346	5,345	45%	17,223
3.3	Outfitting	1,262	38	1,300	100%	2,599
	Building & Outfitting Sub-total	**18,070**	**542**	**10,720**	**58%**	**29,332**
4.0	**Project Management**	**2,985**	**805**	**948**	**25%**	**4,738**
5.0	**Additional Contingency**	**-**	**-**	**14,145**		**14,145**
	due to the early stage of the cost estimate					
TPC	**Total Project Cost**	**101,570**	**8,263**	**54,916**	**50%**	**164,749**

Near Term Program Goals

- MiniBoone
  - Continue high efficiency operation
    - First oscillation results should be ready by end of 2005
    - Cross-section measurements on same time scale
  - Continue Running in 2006
    - Choose neutrino or anti-neutrino running based on oscillation results
    - All hardware for the polarity switch is on-site and can be installed in ~ 2 weeks
    - 1 year of anti-neutrinos will yield significant cross-section measurements, but not appearance oscillation results
  - Collaborating with K2K collaboration to install Scibar (15 ton fine grained) detector in a yet to be determined near location
    - Working on physics study
      - Optimize detector location by balancing cost & physics
      - Measure nu contamination in anti-nu mode
      - Measure final state details
      - Very similar energy to T2K beam - Xsec measurement
      - Near detector for MB
    - Keep cheap! (~ $200k-$400k)
    - Move fast! Scibar needed back in Japan in 2008/9

Near Term Program Goals

- MINOS
  - Resume NuMI beam operations
    - Run until 2005 Indian Summer shutdown
    - Aim to accumulate ~1e20 POT
      - Should be dozens of events in the Far Detector
  - Run 2006 through 2009
      - Proton intensity should increase from 2.5e13 to 4e13 ppp
      - Goal by 2008 : 3-3.4e20 POT/year
  - Continue to collect atmospheric neutrino events in the Far Detector

Near Term Program Goals

- MINERvA
  - Vertical Slice Test (2) [scintillator thru DAQ]
  - Answer design optimization questions
  - Complete all R&D to be ready to use construction funds at beginning of FY07
  - Begin data taking July 2008
- NOvA
  - Begin site development design (environmental impact)
  - Design prototype/Near detector
    - 20 ton fiducial, (260 ton total) in MINOS Near Surface Building

In a broader context....

- Fermilab scientists are participating in conceptual design studies for future facilities and detector technologies, i.e.
  - Large scale Liquid Argon TPC (FLARE)
  - Small scale exposure of OPERA bricks in the MINOS Near Hall (PEANUT)
  - Reactor experiments to measure θ_{13}
  - Deep underground facilities at large distances (DUSEL)
    - Eye towards developing a synergy between a super neutrino beam-long baseline experiment with a super detector which could do proton decay and super nova physics
- These activities enable us to participate in, and more fully contribute to the development of a road map for the future of neutrino physics.

PPD Neutrino Department

- Completion of the NuMI/MINOS Project, and hence the Project Organization, required a reassignment of the manpower resources which had been assigned to the Project
  - AD NuMI Project Office ⇒ AD Proton Plan Project Office
  - AD NuMI Department ⇒ AD External Beams Department
  - PPD MINOS Department ⇒ ?
- Used this opportunity to strengthen the support for the overall Laboratory Neutrino Program
  - Gathered together scientific staff whose primary research and service work is MiniBoone, MINOS, MINERvA, or NOvA
  - Department Head (Rameika/MINOS)
  - Deputy Department Head (Brice/MiniBoone)

PPD Neutrino Dept. (con't)

- Department has 17 staff
  - 10 Scientists
  - 1 Associate Scientist
  - 2 Applications Physicists
  - 1 Engineering Physicist
  - 3 Research Associates (MINOS)
- Many members hold key roles in the physics program
  - 2006 MiniBoone co-spokesperson (S. Brice)
  - MINOS Run Coordinator (R. Plunkett)
  - MINOS Near Detector Operations Manager (P. Shanahan)
  - MINERvA co-spokesperson (J. Morfin)
  - MINERvA Project Manager (D. Harris)
  - NOvA co-spokesperson (J. Cooper)
  - DUSEL LBL co-working group leader (R. Rameika)
  - DUSEL and Theta13 underground consultant (C. Laughton)

PPD Neutrino Dept. (con't)

- Department Functions
  - Line organization/administrative home for Fermilab staff
  - Manage experiment R&D, construction and operating budgets
  - Maintenance support for experimental halls and control rooms
    - MiniBooNE - 10 SW
    - MINOS - 12 NW
  - Provide administrative support to the User Community
    - Office space, housing, visitor support…
    - Assist with collaboration meetings held at Fermilab

We currently have a large, active group of Staff and Users working on our current and future Neutrino Experiments

The Next Generation of Questions

- *What are the masses of neutrinos?*
- *What is the pattern of mixing among the different types of neutrinos?*
- *Are neutrinos their own anti-particle?*
- *Do neutrinos violate the symmetry CP?*
- *Are there "sterile" neutrinos?*
- *Do neutrinos have unexpected or exotic properties?*
- *What can neutrinos tell us about the models of new physics beyond the Standard Model?*

From the APS Multi-Divisional study on the Physics of Neutrinos

More Questions than answers..

- Why do neutrinos have tiny masses, and how do they transform into one another?
- Are the existence and stability of ordinary matter related to neutrino properties?
- Are there additional types of neutrinos?
- What is the mysterious dark matter, and how much of it consists of neutrinos?
- What role do neutrinos play in the synthesis of the elements in the periodic table?
- Is there a deeper simplicity underlying the forces and particles we see?

From the National Research Council's *Neutrinos and Beyond*
In the chapter "Science Potential of a Deep Underground Laboratory"

"There has been a growing recognition of the important role played by neutrinos in answering some of the most compelling questions in subatomic physics. Two National Research Council studies, *Quarks to the Cosmos*, *Neutrinos and Beyond*), two long range planning exercises (HEPAP and NSAC), and most recently a multi-divisional year-long American Physical Society (APS) study have all identified compelling discovery Opportunities involving neutrinos. These studies have laid the Scientific groundwork for the choices that must be made during the next few years. They did an excellent job of explaining the new paradigm of neutrino science, why this science is filled with important and interesting questions, and why **the time is right to address these questions**."

Charge letter from Kovar (DOE-NP), Staffen (DOE-HEP) and Turner (NSF) to form Neutrino Science Assessment Group (NuSAG)

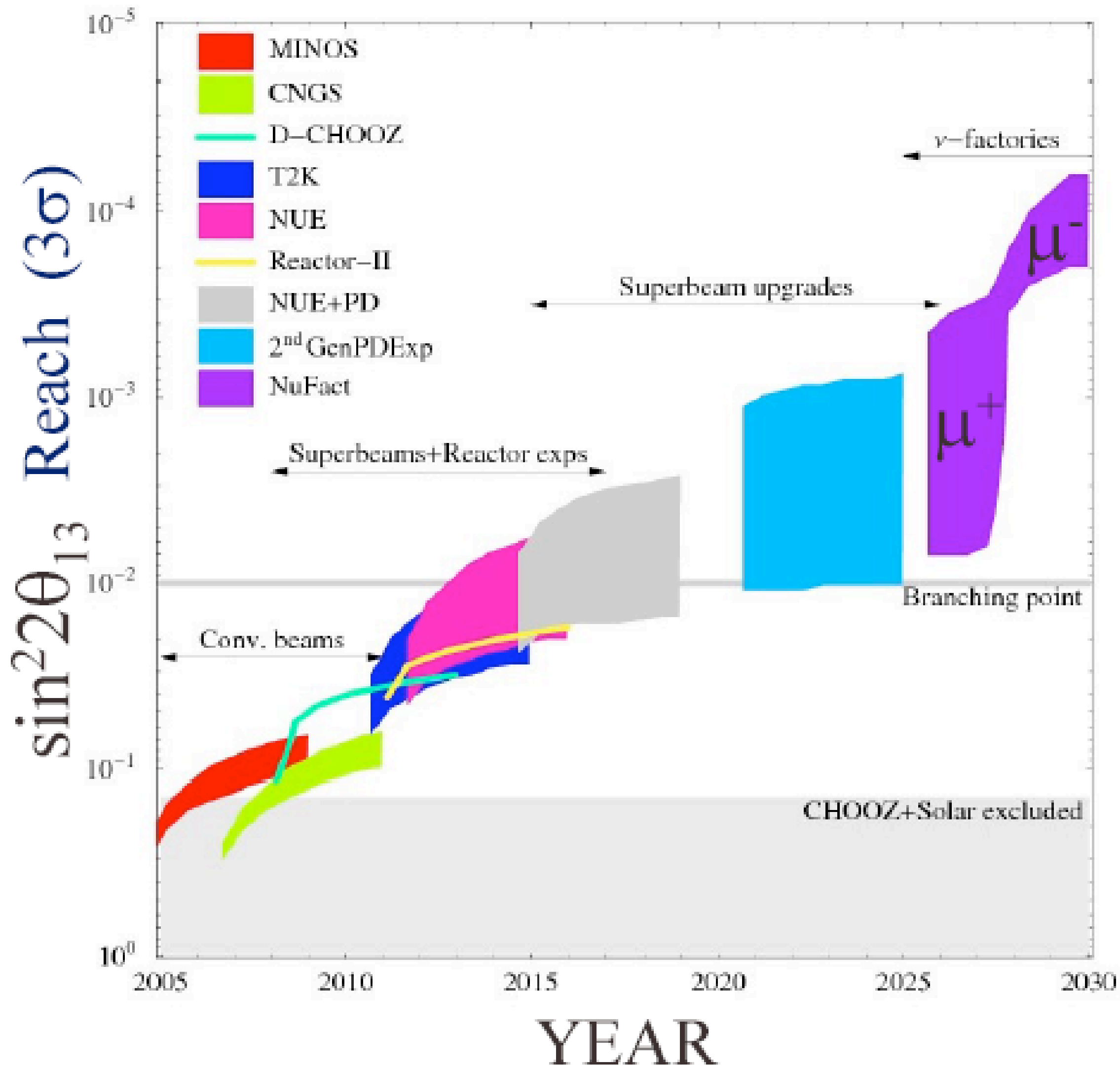
Long Term Scenarios

- More detail in Steve Geer's talk tomorrow

Accelerator based neutrino experiments need protons.

Several ways to Achieve this :

Incremental Improvements (Proton Plan);
New facility (PD)
New technologies (Neutrino Factories)



Summary and Conclusions

- Fermilab is currently host to two world class neutrino experiments, MiniBooNE and MINOS
  - Continued operation of MiniBooNE will provide clear resolution of the LSND results
  - Improvements in MI proton intensity will insure that the physics reach of the MINOS experiment is maximized
- This program can expand in the near future with the MINERvA and NOvA experiments, exploiting the major investment made in the NuMI facility
- Fermilab scientists play key roles in the scientific leadership and project management of the entire neutrino program

Summary and Conclusions (con't)

- Our 1995 vision of what we should be doing in 2000, is quite different than what we find ourselves doing in 2005…
- ≥10 year time scales for the proposal, design and construction of new facilities and experiments require that we keep our eyes on the physics at all times and be able to react/adapt to new results and discoveries.
- The newly formed PPD Neutrino Department, in collaboration with scientists throughout the Laboratory and the Fermilab User Community, is well poised to take the lead in the development of a well focused, evolutionary program of experiments that will take us into the next decade, and perhaps beyond, as we continue to find the answers and ask the questions.